Hidden Wind Farms Potential for Residential Households Having Roof-mounted Wind Arrester

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Abstract—**Small-scale energy-generating systems are being increasingly integrated into built environment, and the use of renewable energies is now spreading to old towns in developing countries. Despite the promise of free energy, the high-tech appearance of the harnessing tools of renewables has provoked criticism because of the incompatibility with the cultural/environmental characteristics of older towns in Iran. This paper presents a new concept of novel hidden wind farms in the residential households of Iranian desert-edge towns with roof-mounted wind-arresters. The results of this study show that a hidden wind farm integrated into old towns with the potential of tourism can eliminate the concern over the visibility and bird collisions as well as the use of land. In the present study, the old city of Ardakan, Yazd, with an arid climate located at the edge of a desert in the center of Iran, is selected as target case study. Calculations show that the application of one small-scale wind turbine per wind-arrester across the town can generate approximately 2.90 GWh a year. Moreover, the proposed concept could also be applied in other countries such as Afghanistan, Egypt, Pakistan, Iraq, UAE and some African countries.**

Keywords—built enviornment; small-scale wind turbine; wind-arrester; hidden wind farm; Iran

I. Introduction

Living in the desert requires personal as well as interpersonal adaptability to the environment. The traditional architecture of Iran is an example of organic architecture and is thus formed with extreme respect to the local ecosystems and geophysical specification of the earth [1]. Iranian desert architecture enjoys a great number of traditional sustainable solutions in response to energy consumption within an arid climate, for instance, domes, water reservoirs, lofty walls and narrow streets [2]. One of the most effective solutions is to utilize the blowing wind in order to either generating power employing various proposed systems [3-5] or cooling a building. For the latter approach, the wind-arresters (bâdgir) have served as a passive cooling system for a long time, as is shown in Fig. 1. The wind-arrester, as its name denotes, is considered a part of a building form customarily constructed in any hot and dry or humid area of Iran and it plays an effective role in modifying heat and adjusting the temperature of interior living spaces [6]. To achieve natural ventilation in roofs, wind-catchers are essential. Wind-catchers are important when trying to acquire a desirable wind flow at roof level through its entrance at the top and direct it downward as is shown in Fig. 2. On the contrary, if the wind hits the opposite side of the entrance the positive pressure on the windward side and negative pressure on the leeward side will suck the hot and pollutant air to the outside of the building. As is shown in Fig. 3, in the absence of the wind, wind-catchers' function is based on the temperature differences. At night, lower outside temperatures makes the air flow inside; it warms up by heated walls, then moves upward through out of the building, and vice versa during the days.

The first historically documented Iranian wind-arrester dates back circa 4000 BC, and this cooling system has been utilized in other countries such as Afghanistan, Egypt, Pakistan, Iraq, and UAE over the past centuries [7].

The distributed generation is a small-scale generation with a capacity below 50-100 kW (for domestic installations <3 kW), which is distributed and used over a local area such as homes and farms [8]. Nowadays small-scale generating systems are normally integrated into the built environment of old towns in developing countries, which are now increasingly resorting to renewable energies. In spite of the fact that finding an energy source more benign to the environment than wind power is impossible, a serious obstacle facing the development of wind industry in old towns is public opposition, reflecting concern over the visibility and noise of wind turbines as well as the use of land. Another concern of note is the incompatibility of the wind industry with the cultural/environmental characteristics of old towns.

Fig. 1. Ardakan wind-arresters on the roof of the houses

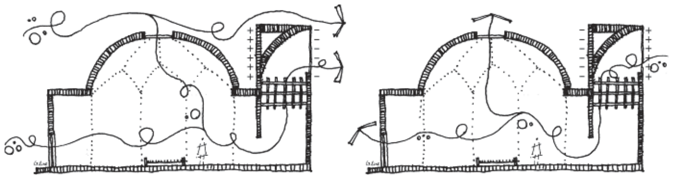

Fig. 2. Wind-arrester ventilation

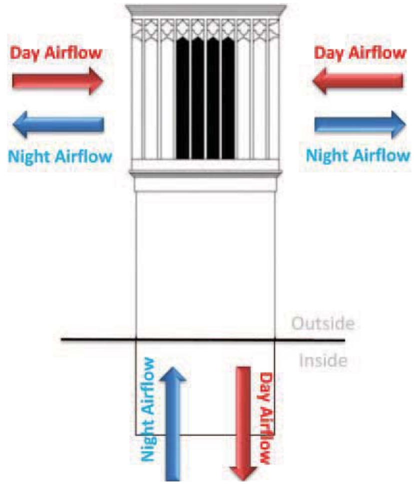

Fig. 3. Wind-arrester function in the absence of the wind

This paper presents a new concept of novel hidden wind farms in residential households having roof-mounted wind-arresters in Iran. The validity of the proposed concept was tested by the selection of the old city of Ardakan, Yazd, in an arid climate as our case study. The results show that a hidden wind farm integrated into old towns with the potential of tourism can eliminate the concern over the visibility and noise of wind turbines as well as the use of land. The measurements reveal that the wind speed at the bottom of the wind-arrester would be 50% faster than the wind velocity at the entrance of the wind-arrester. Moreover, our calculations demonstrate that the application of one small-scale wind turbine throughout the town can generate approximately 2.90 GWh a year.

II. ARDAKAN SITE

A. Description of Ardakan Site

Ardakan is an old desert-edge town located sixty kilometers far from Yazd. Ardakan has a hot and arid climate and boasts a great number of wind-arresters: approximately 1180 wind-arresters lie in 540000 square meters, which means each building has at least one wind-arrester. Moreover, the differences in temperature of as much as 25°C (77°F) between day and night occur regularly in this area.

B. Wind Charactrestics

Regarding the database of Renewable Energy Organization of Iran, an anemometer with a sampling rate of 10 minutes provided the wind speed data at a height of 10 meters in the period from September 27, 2006 to February 20, 2008 in Ardakan weather station [9]. The average wind speeds in twelve months of 2007 is shown in Table I. Wind rose at

TABLE I. AVERAGE WIND SPEED IN 2007

Month	***Jan.***	***Feb.***	***Mar.***	***Apr.***	***May***	***Jun.***
Ave. Wind Speed (m/s)	2.3	3.32	4.3	3.25	3.8	4.5
Month	***Jul.***	***Aug.***	***Sept.***	***Oct.***	***Nov.***	***Dec.***
Ave. Wind Speed (m/s)	5.5	2.83	2.7	2.6	2.8	2.85

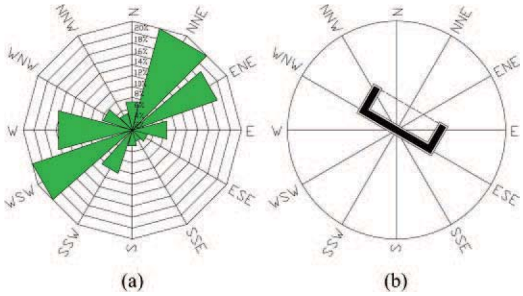

Fig. 4. Wind rose (a) , and wind-arresters direction (b)

Ardakan was obtained from a previous study [9]. The dominant wind directions were NNE and WSW, as is shown in Fig. 4 (a).

C. Direction of Wind- arresters

The two dominant winds in Ardakan differ in quality: the wind blowing from NNE is desirable for the residents on account of the fact that it carries cool and fresh air from the northern part of Iran, whereas the wind from WSW bears dust particles and is thus named "black wind" [10]. As a result, previous generations of architects laid the wind-arresters exposed to the NNE dominant wind and sheltered the three other faces. This kind of wind-arresters, referred to as the "one-sided" wind-arrester [11], is depicted in Fig. 4 (b).

III. NEW CONCEPT

A. Concept Definition

We found wind-arrester the most optimal means for generating electricity by wind energy, which is led through the towers and into the interior space of buildings. This concept is the first of its kind to propose the installation of wind turbines in wind-arrester towers in the form of a wind farm concealed from public view for electricity generation. The lowest part of a wind-arrester tower, which channels the wind into the house, would be the optimum place to install a wind turbine inasmuch as the wind velocity is at its highest level.

Unlike common wind farms, the concept introduced herein not only does not require wind turbines allocation, with the ones having hitherto been built by generations of architects being a testament, but also obviates the existing concern over the visibility and bird collisions as well as the use of land in that such wind turbines would be installed inside the existing wind-arresters.

B. Effective Wind Speed

The measurements reveal that the wind will accelerate from the entrance at the top of the wind-arrester to downward. To find out the acceleration factor accurately, we measure the wind velocity at the entrance of the wind-arrester (V_{Up}) and at the lowest part of the wind-arrester tower (V_{Down}) simultaneously by hot-wire anemometers. The acceleration factor (A.F.) is equal to:

$$A.F. = \frac{v_{Down}}{v_{Up}} \tag{1}$$

These measurements were done for six different wind-arresters in Ardakan region during November 2012, January, May and April 2013. As is shown in Table II, the results of four experiments are given as example in detail to cal. As is shown in Table III, according to the 80 experiments results, the acceleration factor varies from 1.3 to 5. Mode of these data would be 1.5, which returns the most frequently occurring factor. In other words, the wind velocity would accelerate 50% by passing the wind-arrester, as is depicted in Fig. 5.

TABLE II. SAMPLE EXPERIMENTS' RESULTS

No.	V_{Up}	V_{Down}	A.F.	Date
1	7	11	1.57	Nov. 30, 2012
2	0.8	2.5	3.12	Jan. 09, 2013
3	1	5	5	Apr. 14, 2013
4	4.5	6.5	1.44	May 18, 2013

TABLE III. 80 EXPERIMENTS' RESULTS

No.	*A.F.*	*No.*	*A.F.*	*No.*	*A.F.*	*No.*	*A.F.*
1	1.18	21	1.41	41	1.67	61	2.27
2	1.2	22	1.43	42	1.70	62	2.62
3	1.28	23	1.5	43	1.87	63	2.86
4	1.33	24	1.5	44	1.95	64	3
5	1.33	25	1.57	45	1.97	65	3.13
6	1.33	26	1.57	46	2	66	3.75
7	1.38	27	1.58	47	2.03	67	4
8	1.39	28	1.59	48	2.04	68	5
9	1.41	29	1.60	49	2.13	69	5
10	4	30	2.1	50	1.38	70	4.10
11	1.32	31	1.39	51	2.35	71	1.47
12	1.56	32	3.1	52	1.75	72	3.20
13	2.86	33	1.45	53	1.33	73	1.55
14	1.3	34	1.35	54	1.95	74	1.65
15	3.1	35	4.3	55	1.65	75	1.45
16	1.48	36	2.68	56	3.12	76	1.45
17	2.58	37	1.48	57	1.69	77	1.36
18	1.33	38	1.56	58	3.1	78	1.50
19	1.35	39	1.68	59	4.12	79	3.55
20	3.1	40	1.31	60	1.78	80	1.45

Therefore, as is shown in Table IV, effective wind speeds in each month of 2007 would be obtained by applying the acceleration factor in the mentioned velocities of Table I. Fig. 6 shows the profound effect of the wind-arrester on the wind velocity in each month of 2007.

C. Selection of a Sample Wind-arrester

The Ardakan wind-arresters are shaped as a rectangular prism. In this case, a sample wind-arrester, 1.6 m (width) ×4 m (length) ×10 m (height) in size, is chosen as the most prevalent one.

D. Selection of a Wind Turbine

Wind turbines are classified into three different categories according to the types incorporated within the environment [12]: building-integrated; building-mounted; and building-augmented wind turbines.

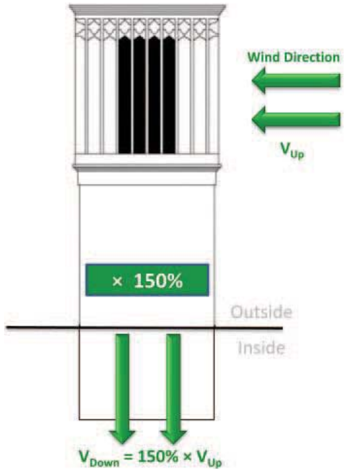

Fig. 5. Acceleration of the wind velocity by passing the wind-arrester

TABLE IV. EFFECTIVE WIND SPEED IN 2007

Month	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*
Eff. Wind Speed (m/s)	3.45	4.85	6.45	4.88	5.7	6.75
Month	*Jul.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Eff. Wind Speed (m/s)	8.25	4.25	4.1	3.9	4.2	4.28

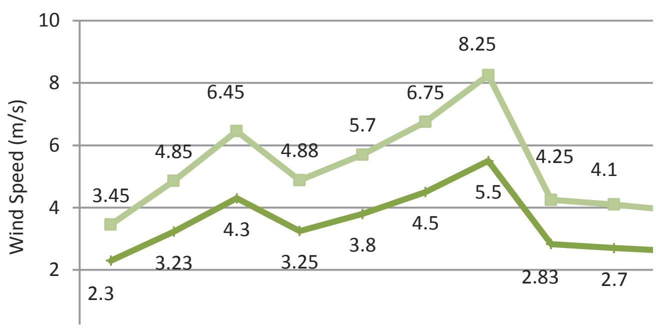

Fig. 6. Effect of the wind-arrester on the wind velocity

Building-augmented wind turbines are incorporated into the design and construction of the buildings as part of the architecture. There are mainly two methods to implement [8]. One method is to shape the building in an aerodynamic way as a concentrator so as to acquire an enhanced airflow around the rotor and thus augment the flow through the turbines [14], as is shown in Fig. 7 (a). Another method is to create a duct that utilizes the pressure difference between the windward and the leeward side of the building [13,14], as is depicted in Fig. 7 (b). The concept presented in the present paper proposes the incorporation of wind turbines within the built environment as augmented wind turbines, with a prominent distinction that it would employ the wind-catcher tower as a duct itself; therefore, it would be a hybrid of the two above-mentioned methods. As is illustratrated in Fig. 8, given the dimensions of the sample wind-arrester, wind velocity, and bidirectional nature of the wind, the savonius wind turbine was chosen as an appropriate model.

E. Installation

In regard to the weakness of adobe walls in the desert-edge town buildings and the weight of the turbine, the installation of a wind turbine in the wind-arrester would need reinforcement of the latter by a concrete structure, as is shown in Fig. 8. This structure would transfer the weight of the turbine into the ground through the concrete wall, which lies in the bottom part of the wind-arrester.

F. Electrical Equipment

The electrical circuit, which is used for generation, transfer, and storage, consists of a savonius wind turbine, a wind controller which must be robust and non-singular [15-17], battery banks, DC loads, an inverter, and AC loads. The diagram of this circuit is depicted in Fig. 9.

IV. CALCULATIONS

A. Generation Data

The technical features of "FDCS-15B (1350W)" are explained in Table V. The "FDCS-15B" turbine power curve with a steady wind speed is illustrated in Fig. 10. Data on the output by the applied wind turbine in every single month of 2007 were calculated, as is shown in Table VI. The proposed wind turbine would, therefore, yield a high output at a low wind speed but with a very low level of noise.

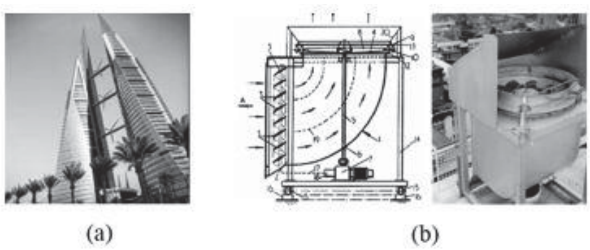

Fig. 7. Augmented wind turbine (a), and augmented equipment [9] (b)

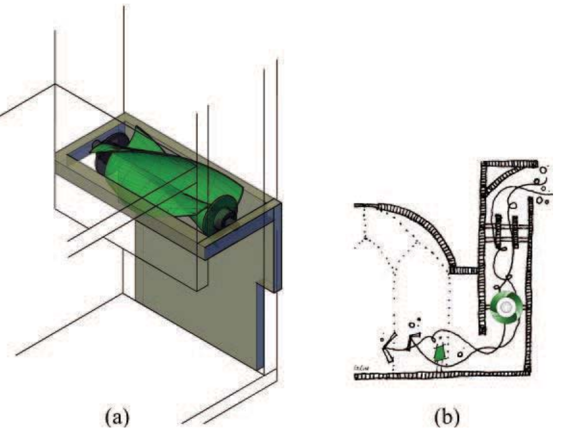

Fig. 8. Turbine position in wind-arrester (a) ,and the section (b)

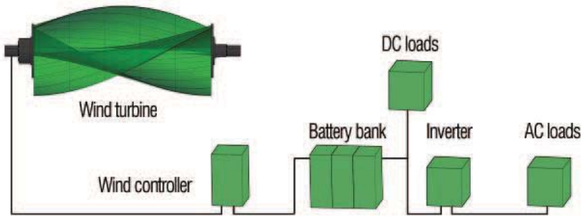

Fig. 9. Diagram of the circuit

B. Comprarison between Consumption and Generation

Approximately, 235 kWh per month would provide enough energy to power an average Ardakan home. As is shown in Fig. 11, the application of a small-scale wind turbine in the lowest part of a wind-arrester tower would be effective on the grounds that one wind turbine could generate enough electrical power supply even for two homes in some months.

C. Total Power Generation of Ardakan

According to Table I, the average wind speed was 3.39 m/s in 2007. By applying the acceleration factor of 1.5 in average wind velocities per day [18], it will reveal that we had 240 days in 2007 which had an effective wind speed greater than the cut-in of the "FDCS-15B". Given the increase of the wind speed through the wind-arrester, as is calculated in (2), and the generation of 5760 hours a year, the installation of one small-scale wind turbine in 900 wind-arresters, which have adequate space for the selected wind turbine, across the town could generate the following output in one year as shown in (3). Moreover, the capacity of the hidden wind farm would be 504 kW as is calculated in (4).

$$3.39\ m/s \times 150\% = 5.08\ m/s \tag{2}$$

$$900 \times 559.5\ W \times 5760\ h = 2900.45\ MWh/year \tag{3}$$

$$900 \times 559.5\ W = 503.55\ kW \tag{4}$$

TABLE V. TECHNICAL FEACHURES OF TURBINE

Item	Feature
Type	Savonius wind turbine, VWAT
Rated power	1350 W (14 m/s)
Rotor diameter	1.5 m
Blade length	3 m
Blade material	Foam
Cut-in /Cut-out wind speed	3.0 m/s / 35.0 m/s
Blade weight	135 kg

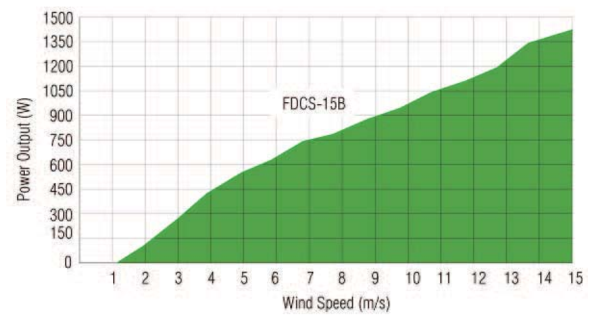

Fig. 10. Generation characteristic curve of the applied wind turbine

TABLE VI. TURBINE GENERATION IN 2007

Month	***Jan.***	***Feb.***	***Mar.***	***Apr.***	***May***	***Jun.***
Power Output (kWh)	248.8	386.6	501.1	388.8	441.7	527
Month	***Jul.***	***Aug.***	***Sept.***	***Oct.***	***Nov.***	***Dec.***
Power Output (kWh)	596.1	337	324	303.5	330.5	337.7

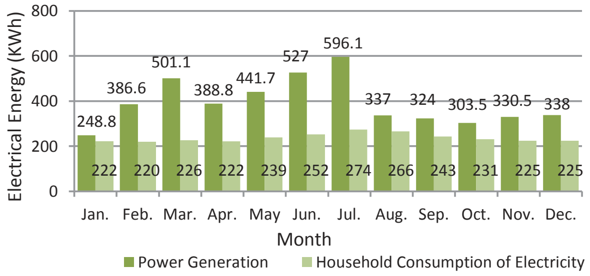

Fig. 11. Comparision between consumption and generation of a house

V. CONCLUSION

In this paper, a new concept has been defined for novel hidden wind farms in residential households having roof-mounted wind-arrester in Iran. The results reveal that the application of small-scale wind turbines for houses with wind-arresters would have the following advantages:

- Installation of a small-scale wind turbine inside each wind-arrester tower could create a hidden wind farm in old desert-edge towns with the potential of tourism in harmony with the cultural/environmental characteristics.
- The proposed hidden wind farm would be integrated into the built environment to eliminate the concern over the visibility and noise of wind turbines as well as the use of land. Moreover, it would be bird and bat-friendly.
- The proposed wind farm would comprise wind turbines incorporated within the built environment in the form of building-augmented wind turbines, with the advantage that the wind-arrester towers would serve as ducts themselves.
- In contrast to wind farms, the proposed wind farm would obviate the need to perform wind turbines allocation insofar as they would be mounted in previously built wind-arresters, which have stood the test of time.
- Small-scale wind turbines could be employed in any house with a wind-arrester to meet all or more than the electricity need of a building.
- The proposed concept could also be applied in residential households having roof-mounted wind-arrester in other countries such as Afghanistan, Egypt, Pakistan, Iraq, and UAE.

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